

**INCREASING THE PERFORMANCE OF AIRCRAFT ON-BOARD INERT
GAS GENERATING SYSTEMS BY TURBOCHARGING**

[0001] This application claims priority pursuant to 35 U.S.C. § 120 to U.S. Application No. 10/308,973, filed December 3, 2002, which application is based on U.S. Provisional Patent Application Serial No. 60/416,177, filed October 4, 2002, and to U.S. Application No. 10/308,971, filed December 3, 2002, which application is based on U.S. Provisional Application No. 60/392,909, filed June 28, 2002, the specifications of which are incorporated herein by reference in their entireties

**BACKGROUND OF THE INVENTION
FIELD OF THE INVENTION**

[0002] This invention relates to a method and apparatus for improving aircraft safety. More specifically, it relates to an apparatus and method for preventing combustion in aircraft fuel tanks and cargo spaces by supplying inert gas using turbocharged engine bleed air.

DESCRIPTION OF THE RELATED ART

[0003] Military aircraft have used On-board Inert Gas Generating Systems (OBIGGS) for some years to protect against fuel tank explosions due to undesired phenomena, such as penetration from small arms fire. Military aircraft are not the only aircraft that would benefit from OBIGGS. For example, investigations into the cause of recent air disasters have concluded that unknown sources may be responsible for fuel tank ignition and explosion. Subsequently, OBIGGS has been evaluated as a way to protect commercial aircraft against such fuel tank explosions started by unknown ignition sources.

[0004] OBIGGS protects against fuel tank explosions by replacing the potentially explosive fuel/air mixture above the fuel in the tanks (the ullage) with an inert gas (usually nitrogen - N₂). The nitrogen is generated by separating oxygen from local, ambient air and pumping the inert product into the tanks.

[0005] In previous applications, OBIGGS has proved relatively unreliable, heavy, and costly for both initial acquisition and operation in aircraft. Furthermore, military aircraft systems often have the strict requirements that derive from military flight profiles that include high-rate descent from high-altitude flight. Applications of OBIGGS to commercial aircraft would benefit by considering the fact that a typical flight profile for the

commercial application has a less demanding requirement for the system because commercial aircraft do not operate at the same flight profiles of military aircraft.

[0006] Thus, there is a need for a gas generation and inerting system that minimizes the quantity and complexity of sub-components (particularly moving parts). The system should also consider a typical commercial aircraft flight profile and take advantage of the reduced descent rates (compared to military aircraft).

SUMMARY OF THE INVENTION

[0007] The present invention provides an apparatus and method for reducing the possibility of combustion in aircraft fuel tanks by replacing air in the ullage of the fuel tank with an inert gas that has been separated from the engine bleed air. The apparatus includes an air separation module, a filter, a heat exchanger, and a rotary compressor and turbine (or “turbocharger”). In this invention, the turbine is powered by a flow of nitrogen-enriched air from the air separation module and drives the compressor through a shaft and the compressor creates an increased engine bleed air pressure for the air separation module. In one preferred embodiment, a single housing contains at least the air separation module, filter, heat exchanger, and turbocharger. The air separation module can be mounted in a center-section of the housing, may be a canister-type design, may include a replaceable cartridge, and may be a hollow-fibre permeable membrane configuration.

[0008] The method of the present invention includes displacing the atmosphere in the ullage of a fuel tank with a non-combustible gas. In one embodiment, the method comprises compressing engine bleed air and subsequently supplying it to an air separation module that generates a non-combustible nitrogen-enriched air. This method also includes providing at least one modular unit capable of producing a flow of nitrogen-enriched air at a predetermined flow rate and oxygen purity level; sizing the modular unit based on compressed engine bleed air; grouping a number of the modular units sufficient to meet the aircraft’s inert gas requirement with a combination of said predetermined flow rates. Preferably, the introduction of high-purity non-combustible gas occurs during take-off and level flight of an airplane and introduction of the lower-purity gas occurs during descent of the airplane.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0009] The foregoing and other aspects and advantages of the present invention will be better understood from the following detailed description when read in conjunction with the drawings, in which:

[0010] FIG. 1 is a schematic view of one embodiment of a modular on-board inert gas generating system according to the present invention;

[0011] FIG. 2 is a schematic view of an alternative embodiment of the invention;

[0012] FIG. 2A is a schematic view of an alternative embodiment of the invention based on the embodiment in FIG. 2;

[0013] FIG. 3 is a cross-sectional view of a modular system according to the invention;

[0014] FIG. 3A is a cross-sectional view of another modular system according to the invention;

[0015] FIG. 3B is a schematic view of a modular system employing multiple modules according to the invention;

[0016] FIG. 4 is a perspective view of an embodiment of the invention;

[0017] FIG. 5 is a schematic view of an additional alternative embodiment of the invention; and

[0018] FIG. 6 is a cross-sectional view of an alternative embodiment of the invention of FIG. 5.

[0019] Like numerals refer to similar elements throughout the several drawings.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0020] As illustrated in FIG. 1, system 10 according to one embodiment of the invention uses aircraft engine bleed air 12 that is supplied under conditions of elevated temperature and elevated pressure to generate gas for inerting aircraft fuel tanks. It will be appreciated by persons skilled in the art that the present invention is equally useful for inerting cargo holds and other void spaces. Engine bleed air is typically supplied from taps in the turbine section of the aircraft engines at temperatures in the range of 300°F - 400°F and at pressures in the range of 10 - 45 psig depending on turbine rotation speed. It is typically used as a utility source of pressurized air on board aircraft. System 10 operates whenever bleed air is available and, thus, avoids the use of compressors or complex control valves.

[0021] Bleed air 12 is introduced at one end of system 10 and nitrogen-enriched air (NEA) is produced from the other end. Bleed air 12 flows under pressure and temperature to heat exchanger 14. A branch passage taps off a small portion of the pressurized bleed air to power jet pump 16. For efficient operation, depending on size, air separation module (ASM) 18 requires input air temperature in the range of less than 200°F. Heat exchanger 14 is therefore used to control the temperature of the engine bleed air fed into ASM 18.

Secondary cooling flow 20 is provided to heat exchanger 14 for this purpose. Jet pump 16 may be utilized to provide the cooling flow, which is vented overboard at outlet 22. If desired, temperature sensor 24 may be positioned down stream of the heat exchanger to monitor output temperature and control secondary flow 20, and/or jet pump 16 based on the monitored temperature.

[0022] The pressurized air flow from heat exchanger 14 enters filter 26. Filter 26 may comprise multiple filters, such as a coalescing filter to remove particulate contaminants and moisture, and a carbon filter for removing hydrocarbons. Filter drainpipe 28 drains removed moisture and directs it overboard at outlet 22.

[0023] After leaving filter 26, the conditioned air enters ASM 18. Preferably ASM 18 provides a total flow in the range of approximately 2 - 4 lbs./min., with a pressure drop of a few psig. Depending on aircraft requirements or other system limitations, other sizes of ASM may be selected. Using conventional hollow-fiber technology, ASM 18 separates the air into oxygen-enriched air (OEA) and nitrogen-enriched air (NEA). In a preferred embodiment, the ASM provides nitrogen-enriched air at flow rates between about 0.5 lbs./min. up to about 2 lbs./min. At the lower flow rates a greater nitrogen purity can be achieved, with oxygen making up only about one percent by volume of the nitrogen-enriched air. At higher flow rates the oxygen content of the nitrogen-enriched air is typically about nine to ten percent by volume. Oxygen-enriched air is piped from ASM 18 overboard through outlet 22. Check valve 29 is provided in the overboard OEA line to prevent back-flow. Nitrogen-enriched air produced by ASM 18 is directed to the fuel tank and/or cargo hold. Orifice 30 is preferably provided downstream of ASM 18 to control the flow rate through the ASM. If desired, a stepped or variable orifice may be provided to control flow rate as described in greater detail below. Optional oxygen sensor 32 may be configured to provide signals representing oxygen content of the NEA and may be utilized for orifice control. Another optional sensor that may be provided is mass air flow sensor 34. This may be an automotive-style hot wire mass-flow sensor. System outlet 36 directs the NEA to the fuel tank ullage and optionally to aircraft cargo hold as desired.

[0024] In an alternative embodiment illustrated in FIG. 2, engine bleed air first passes through an isolation valve 38. Isolation valve 38 permits system 10a to be isolated from the bleed air and, if desired, may be controlled by signals from temperature sensor 24. In this embodiment secondary cooling air is provided by an NACA scoop 40. A ram air scoop may also be used to provide secondary cooling air. Secondary cooling air passes through temperature modulation valve 42, which also may be controlled by temperature sensor 24. Alternatively, temperature control of the primary bleed air flow may be achieved

through a modulated by-pass flow arrangement (described in detail with reference to FIG. 2A). Secondary cooling air obtained from scoop 40 typically will have a temperature ranging from about -60°F to 110°F or greater, depending on the environmental conditions experienced by the aircraft. The secondary air flow again passes through heat exchanger 14, optionally assisted by jet pump 16. Operation of filter 26 and ASM 18 is essentially as described above. In this exemplary embodiment, an orifice is provided with two steps or as a stepped choke valve. For example, a first orifice 44 presents an opening of a first size and second orifice 46 presents an opening of a second size. The orifice seen by the NEA flow is determined by orifice selector 48, which may be a solenoid actuated valve, or other flow control device. The orifice selector is utilized to control the flow rate as described below. NEA exiting the system optionally passes through a first check valve 50, after which it is directed through the fuel tank or cargo hold bulkhead 52. A second check valve 54 may be provided before the NEA is injected into the fuel tank or cargo hold.

[0025] The embodiments of the present invention as described above take advantage of characteristics of ASM 18 to produce higher purity NEA (lower O₂ content) when flow is restricted. Flow may be restricted using down stream orifices or back pressure. In the embodiments utilizing the variable orifices, preferably two different restrictions are used. Other numbers might be used if warranted by system performance and requirements. A high restriction provides low flow and high purity, and a low restriction provides a higher flow and low purity. These embodiments rely on existing aircraft vent systems to provide normal tank inward and outward venting while mixing the NEA in the tank ullage or cargo hold space. A high NEA outlet purity combined with a longer flow time will result in an ullage gas with a higher NEA purity. During the climb and cruise portion of a flight, the high purity (low flow) NEA is delivered to the fuel tank. This stores a high nitrogen concentration gas in the fuel tank ullage. During the descent portion of the flight, in which more air vents into the fuel tank as altitude decreases, the orifice is set to provide a lower restriction and higher flow, thus producing a lower purity NEA but at greater volume. Because high purity NEA is already stored in the fuel tank ullage, however, air forced in through tank vents during descent simply serves to decrease the nitrogen purity. When supplemented by the high flow low purity NEA provided during descent, the ullage maintains a nitrogen purity sufficient to maintain the inert condition. Given the typical commercial flight profile, although the nitrogen level decreases during aircraft descent, with an appropriately sized system the nitrogen levels can be maintained at an inert level through aircraft landing.

[0026] In further alternative embodiments, the system of the present invention may be designed to eliminate components such as sensors, variable orifices and the jet pump, thereby further simplifying the system and increasing reliability. In one embodiment, orifices 44 and 46, and selector valve 48 are eliminated by sizing the system to meet extreme operating conditions at all times. This may be accomplished by sizing the system to provide sufficient NEA during climb and cruise operation, so that the oxygen level in the ullage remains at below a critical level during descent and landing. Typically, the critical oxygen level will be less than about 10% - 14% oxygen, more particularly less than about 12% oxygen. For example, if a system using the multiple orifices as described above were sized to provide NEA at 0.5 lbs/min with 1% oxygen during climb and cruise, in eliminating the orifices the system may be sized to provide NEA continuously with about 2 % oxygen at a slightly higher flow rate. Factors considered include fuel tank size and aircraft flight profile. The system is then designed to, in effect, store high purity NEA in the fuel tank ullage so that upon inflow of air during descent the critical oxygen level is not exceeded before aircraft operation ceases after landing.

[0027] In another embodiment, jet pump 16 may be eliminated by sizing the system to rely only on ram air from scoop 40 for secondary cooling flow. This has the advantage of further simplifying the system by removing another component with moving parts. This advantage must be balanced with the need for additional ground service equipment to provide cooling for testing and maintenance when the aircraft is not in flight.

[0028] Another variation involves the removal of temperature sensor 24 and temperature modulation valve 42, or primary bypass flow control if this is the solution used. In this embodiment, a maximum hot temperature is assumed based on the expected operating conditions. In typical commercial flight profiles in most parts of the United States this would be about 200°F. ASM 18 is then sized to provide the required purity of NEA based on an input temperature at the assumed maximum.

[0029] With the system sized to produce a minimum known NEA flow and purity, additional sensors such as oxygen sensor 32 and mass flow sensor 34 also may be eliminated. These alternatives for reducing system complexity may be employed alone or in any combination. Exact sizing of the system in the various alternatives described will depend upon the inerting needs and flight profile of the particular aircraft in which the system is to be mounted. A person of ordinary skill in the art will be able to match the system to the aircraft inerting needs based on the disclosure contained herein.

[0030] In FIG. 2A, an alternative embodiment of the invention uses primary heat exchanger bypass flow control to control the temperature of the air entering the ASM inlet.

Bypass valve 43 controls the air flow going into heat exchanger 14. Bypass valve 43 modulates incrementally between being closed and directing all the air flow through heat exchanger 14 and being open, and allowing the unrestricted bypass of heat exchanger 14. The air flow allowed to bypass heat exchanger 14 follows bypass conduit 41 to the air conduit upstream of temperature sensor 24 and filter 26. Temperature sensor 24 is, therefore positioned to determine the temperature of the air entering filter 26 and ASM 18. That temperature is used to direct bypass valve 43 to open and allow an appropriate amount of air to flow around heat exchanger 14 so that the temperature of the air entering filter 26 and ASM 18 is within a desired temperature range. Bypass valve 43 is preferably a phase-change direct acting mechanical sensor and flow control valve. Temperature modulation valve 42 (FIG. 1) and the corresponding control capability are added for additional temperature control if desired.

[0031] As also shown in FIG. 2A, filter 26 may include three sections. As previously described, filter 26 may contain a coalescing and solid containment HEPA filter section, for removing particles and water, and a carbon filter section for hydrocarbon removal. In this embodiment, the filter also includes an additional HEPA filter 27, similar to the first filter section, to prevent carbon filter bits from flaking off the previous filter section and traveling to ASM 18. Subcomponents downstream of ASM 18 may be eliminated as shown in FIG. 2A to reduce cost and complexity. In this embodiment the OEA outlet 76 exits the module to combine with the cooling air flow downstream of the jet pump 16. The filter drainpipe 28 also merges with the cooling air flow downstream of the jet pump 16, but does so within the modular assembly. The embodiments shown in FIG. 2A are otherwise as described with reference to FIG. 2.

[0032] In a further preferred embodiment of the invention, system 10 is provided as a modular assembly as shown in FIGS. 3 and 4. In one embodiment, components such as ASM 18, filters 26 and heat exchanger 14 are provided within common housing 60. Alternatively, housing 60 may encompass only the ASM and filters, with the heat exchanger mounted thereon to form a single modular unit. For example, band clamps 62 may be provided between ASM 18 and filter 26, and filter 26 and heat exchanger 14 to secure the components together.

[0033] At the outlet side, NEA outlet port 64 communicates with the fuel tank ullage. An upper mounting bracket 66 may be provided for securing the unit in an aircraft cargo hold or other appropriate space. At the inlet side, inlet 68 receives engine bleed air 12 and directs it toward heat exchanger 14. Secondary air inlet 70 provides a secondary cooling air flow and outlet 72 communicates with overboard outlet 22. Lower mount 74

also may be provided for securing the unit. As shown in FIG. 4, OEA outlet pipe 76, secondary air flow pipe 78 and filter drainpipe 28 all lead to overboard outlet 22. Oxygen and mass flow sensors may be provided as part of the modular unit, or separately provided, depending on space and installation requirements. Similarly, the orifice and associated control valve may be included in the modular system.

[0034] The single-housing design thus facilitates a simple, lightweight configuration that minimizes both acquisition and in-service costs by eliminating many of the sub-components of a typical military application. By eliminating sub-components the single-housing design will also minimize installation costs when compared to the current distributed component approach. The single-housing design also improves reliability. In preferred embodiments, the filter is arranged to be an easily replaceable, disposable cartridge.

[0035] FIG. 3A shows an additional preferred embodiment of a modular assembly with components contained within a housing 60. In this embodiment, the arrangement of components ASM 18, filter 26, and heat exchanger 14 is changed so that heat exchanger 14 is between filter 26 and ASM 18. This provides better access to filter 26 for maintenance purposes. FIGS. 1 and 2 still describe the function of this embodiment, with the internal plumbing of the various air flows configured to accommodate the component arrangement in FIG. 3A.

[0036] Using the modular approach as described, a module may be designed to provide a particular, predetermined NEA flow rate (where a predetermined flow rate includes a predetermined range of flow rates) and multiple modules may be employed to meet higher flow rate requirements. For example, the individual module may be sized to meet the inerting requirements of a particular customer's smallest aircraft based on the size of the fuel tank, the time available to inert the tank, and the requirements for inerting the tank based on flight profiles. For larger aircraft of the same customer, instead of redesigning the module, multiple modules may be employed to meet the higher flow rate requirements. In this manner, inventory and maintenance costs are reduced because only one type of equipment is required to service an entire fleet of aircraft of different sizes.

[0037] FIG. 3B shows a preferred embodiment of a modular assembly employing multiple modules. In this embodiment five housings 60 each contain an ASM 18, heat exchanger 14, and filter 26, as depicted in FIG. 3A. These housings are plumbed together in parallel. Bleed air 12 is provided to each heat exchanger 14 through a single isolation valve 38 and a manifold 39a. Similarly, manifold 39b provides cooling flow 20 to heat exchanger 14 and manifold 39c collects both the OEA and the post-heat exchanger cooling

air flow and directs it overboard 22. NEA is collected by manifold 39d and directed to system outlet 36 and the fuel tank ullage.

[0038] A further embodiment of the invention boosts system flow performance by tapping bleed air from the high-pressure segment of the aircraft's Air Cycle Machine (ACM). Aircraft environmental control systems often use an air compressor to increase bleed air pressure and temperature in the ACM. This can be used alone or in conjunction with a turbocharger to apply a significantly higher pressure to the ASM. The higher pressure increases the flow and /or purity performance of the ASM, resulting in a smaller and less costly ASM for equivalent system performance. Alternatively, for larger aircraft, fewer ASM's may be required using this embodiment, again resulting in reduced costs and reduced complexity.

[0039] In an additional alternative embodiment illustrated in FIG. 5, system 10b performance is improved by boosting the pressure of the air supplied to ASM 18 using a rotary compressor 110 (a part of a "turbocharger"). For ASMs using hollow fiber membrane separators, higher supply air pressure at ASM inlet 17 (relative to the oxygen enriched air pressure at OEA port 19) allows reducing the ASM size while retaining performance equivalent to an ASM with unboosted supply air pressure. This allows a smaller modular OBIGGS to supply the same predetermined NEA flow.

[0040] Producing higher inlet pressures at the ASM inlet usually requires the addition of a compressor, which must be powered by either an electric motor or other power source. Such power is both expensive to produce and difficult to provide for OBIGGS retrofit applications. In this embodiment of the invention, rotary compressor 110 is powered by a turbine 112 that uses the NEA flowing from ASM 18 as its energy source.

[0041] As in FIG. 1, engine bleed air 12 and secondary cooling flow 20 pass directly to heat exchanger 14. Secondary cooling flow 20, provided by means of a ducted ambient air flow, again passes through heat exchanger 14, but then passes directly overboard through overboard outlet 22. Secondary cooling flow 20 is also directed to a heat exchanger 14a. Heat exchanger 14 cools engine bleed air 12 as it passes through. Compressor 110 compresses the cooled engine bleed air and heat exchanger 14a cools the now-compressed engine bleed air. Heat exchangers 14 and 14a are sized to ensure that the bleed air temperature within the compressor is kept relatively low (especially at its discharge) and that the temperature of the air supplied to ASM inlet 17 does not exceed optimum ASM operating limits. Heat exchangers 14 and 14a may be a bifurcated heat exchanger, or two separate heat exchangers, and may be separate or integral to the OBIGGS module. The operation of filter 26 and ASM 18 is essentially as described above.

[0042] The NEA produced by ASM 18 flows through turbine 112, which is mounted on a common shaft 114 within compressor 110. Flowing NEA through turbine 112 serves to reduce the NEA pressure and temperature before delivering NEA to the fuel tank ullage or other location. Flowing NEA through turbine 112 also yields the energy associated with the NEA pressure and flow to turbine 112 which, in turn, transfers the energy to compressor 110 through shaft 114. A preferred embodiment of the invention using the turbocharger as described is shown in cross-section in FIG. 6.

[0043] The size of ASM 18 may be reduced by operating the unit at a higher pressure than is available from bleed air 12. Higher ASM operating pressure is achieved by using the energy in the NEA, associated with its pressure and flow, to further compress the air supplied to the ASM above that of the bleed air pressure. The higher operating pressure improves the performance of the ASM (and potentially its efficiency) due to its increased pressure gradient to the Oxygen Enriched Air (OEA) area. The higher ASM operating pressure is achieved without adding a compressor powered by some external additional means, thus reducing the overall size of the OBIGGS. In a further preferred embodiment, a second rotary compressor, coaxial to rotary compressor 110 and powered by OEA, provides additional power to further compress the engine bleed air.

[0044] In another preferred embodiment, for some flight profiles (such as when the descent portion is relatively steep) the turbocharger is fitted with a co-axial boost motor. This may be powered by electrical or other means, and allows the embodiment to provide additional NEA flow to the fuel tank or cargo area. This embodiment allows the option of obtaining both high flow and high purity NEA during conditions when tank purity could be reduced significantly, such as during the descent. And this embodiment achieves this while using a relatively small ASM, provided the additional power is available. This embodiment may also be useful in military aircraft OBIGGS applications to provide increased system performance during some portions of the flight.

[0045] A further embodiment of the invention boosts system flow performance by tapping bleed air from the high-pressure segment of the aircraft's Air Cycle Machine (ACM). Aircraft environmental control systems often use an air compressor to increase bleed air pressure and temperature in the ACM. This can be used alone or in conjunction with a turbocharger to apply a significantly higher pressure to the ASM. The higher pressure increases the flow and /or purity performance of the ASM, resulting in a smaller and less costly ASM for equivalent system performance. Alternatively, for larger aircraft, fewer ASM's may be required using this embodiment, again resulting in reduced costs and reduced complexity.

[0046] The apparatus and method of the present invention provide a more satisfactory OBIGGS for a number of reasons. The modular approach to the design of the equipment reduces acquisition and installation costs. The cartridge-style filter with quick-release installation features, together with high OBIGGS reliability due to reduced complexity, also reduces operational costs. The methodology of increasing NEA purity in the tank ullage during cruise, together with increased flow / lower purity NEA injection during descent gives all of the benefits of a traditional OBIGGS system with a much smaller, lighter, less costly, more reliable system.